

# Flywheel energy storage—An upswing technology for energy sustainability

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## Abstract

Flywheel energy storage (FES) can have energy fed in the rotational mass of a flywheel, store it as kinetic energy, and release out upon demand. It is a significant and attractive manner for energy futures ‘sustainable’. The key factors of FES technology, such as flywheel material, geometry, length and its support system were described, which directly influence the amount of energy storage and flywheel specific energy. It is very suitable to such applications that involve many charge–discharge cycles and little in the way of long-term storage applications including International Space Station (ISS), Low Earth Orbits (LEO), overall efficiency improvement and pulse power transfer for Hybrid Electric Vehicles (HEVs), Power Quality (PQ) events, and many stationary applications. Design margins, fault protection and containment were considered as three good approaches to solve safety issue. Vacuum enclosures or helium–air mixture gas condition were discussed for solution of windage energy loss. In short, with the aid of new technologies the cost of FES can be lowered and the FES will play a significant role in securing global energy sustainability.

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**Keywords:** Flywheel energy storage; Specific energy; Flywheel factors; Applications; Issues

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## 1. Introduction

It is now accepted that the present production and use of energy pose a serious threat to the global environment and consequent climate change [1]. Accordingly, more and more countries are examining a whole range of new policies and technology issues to make their energy futures ‘sustainable’ [2]. Clearly, as nonrenewable energy source become more scarce, the world is set to make major changes to its energy supply and utilization systems. One significant manner using energy storage unit is very attractive and expected to show up. Flywheel is proving to be an ideal form of energy storage on account of its high efficiency, long cycle life, wide operating temperature range, freedom from depth-of-discharge effects, and higher power and energy density—on both a mass and a volume basis [3–6]. Flywheel energy storage (FES) can have energy fed in the rotational mass of a flywheel, store it as kinetic energy, and release out upon demand. The first real breakthrough of FES was the seminal book by Dr. A. Stodola in

which flywheel rotor shapes and rotational stress were analyzed [7]. The next big milestones were during the 1960s and 1970s when NASA sponsored programs proposed energy storage flywheels as possible primary sources for space missions and FES was proposed as a primary objective for electric vehicles and stationary power back-up [8]. In the years immediately following, fiber composite rotors were built and tested in the laboratory by US Flywheel Systems and other organizations [9,10]. With the development of strong lightweight materials, microelectronics, magnetic bearing systems interest in the potential of flywheels was flourishing. The present designs at US Flywheel Systems (USFS) have been tested and showed power densities at its designed speed 110,000 rpm will exceed 11.9 kW/kg with in-out efficiency of 93% [7]. The University of Texas at Austin has subjected a composite flywheel spinning at about 48,000 rpm to more than 90,000 charge–discharge cycles with no loss of functionality (see Fig. 1) [11]. At the same time a FES delivering 360 MJ energy and 2 MW rated power was also developed by the University of Texas at Austin Center [12].

The objective of this paper is to describe the key factors of flywheel energy storage technology, and summarize its applications including International Space Station (ISS),

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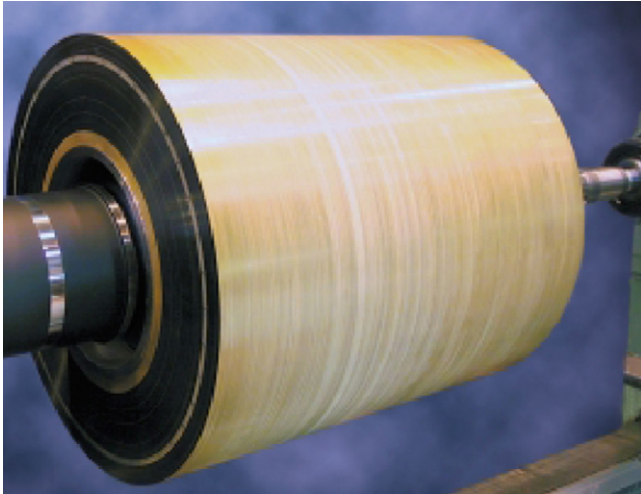


Fig. 1. A flywheel rotor at the University of Texas at Austin's Center.

Low Earth Orbits (LEO), overall efficiency improvement and pulse power transfer for Hybrid Electric Vehicles (HEVs), Power Quality (PQ) events, and many stationary applications, which involve many charge–discharge cycles and little in the way of long-term storage. Eventually, three solutions for safety issues and two approaches for windage loss were also discussed.

## 2. Key factors of FES

### 2.1. Flywheel material

There are two basic classes of flywheels based on the material in the rotor. The first class uses a rotor made up of an advanced composite material such as carbon-fiber or graphite. These materials have very high strength to weight ratios, which give flywheels the potential of having high specific energy. The second class of flywheel uses steel as the main structural material in the rotor. This class not only includes traditional flywheel designs which have large diameters, slow rotation, and low power and energy densities, but also includes some newer high performance flywheels as well.

The amount of energy stored,  $E$ , is proportional to the mass of the flywheel and to the square of its angular velocity. It is calculated by means of the equation

$$E = \frac{1}{2} I \omega^2 \quad (1)$$

where  $I$  is the moment of inertia of the flywheel and  $\omega$  is the angular velocity. The maximum stored energy is ultimately limited by the tensile strength of the flywheel material. The maximum specific (per unit mass) energy density  $E_{sp}$  that can be stored in a flywheel may be written as

$$E_{sp} = K_s \frac{\sigma_m}{\rho} \quad (2)$$

where  $\sigma_m$  is the maximum tensile strength of the flywheel material,  $\rho$  the density of the flywheel, and  $K_s$  is the shape factor. The dependence of  $E_{sp}$  on material properties, i.e.

Table 1  
Physical parameter of commercial fibers

Rotor material	$\sigma_m$ (GPa)	$\rho$ (kg/m <sup>3</sup> )	$E_{sp}$ (Wh/kg)
E-glass	3.5	2540	190
S-glass	4.8	2520	265
Kevlar	3.8	1450	370
Spectra 1000	3.0	970	430
T-700 graphite	7.0	1780	545
T-1000 graphite (projected)	10.0	–	780
Managing steel	2.7	8000	47

proportional to tensile strength an inversely proportional to density, shows we should use a kind of material which has high tensile strength and low density. Fiber composites are the materials of choice for flywheel energy storage systems. Table 1 shows theoretical flywheel energy comparison when  $K_s = 0.5$ . The highest tensile flywheels are not made of steel, but of fiber-reinforced composites. As well as rotating faster and storing more energy than steel flywheels, these composite flywheels are much safer if the maximum safe speed is exceeded, since they tend to delaminate and disintegrate gradually from the outer circumference rather than explode catastrophically [13].

### 2.2. Flywheel geometry

The geometry of an energy storage flywheel is generally chosen in such a way as to maximize the energy density and/or the specific energy [8]. Consider first optimization of the moment of inertia. This would involve placing the mass as far from the axis of rotation as possible and/or increase the density in order to increase  $I$ . Since  $\sigma_m$  is given by

$$\sigma_m = \rho r^2 \omega^2 \quad (3)$$

Flywheels can readily be designed which make optimal use of the material strength. By using Eq. (2) the specific energy  $E_{sp}$  can be calculated for various rotor designs in terms of a shape factor,  $K_s$  for isotropic materials; see Table 2. The shape factor,  $K_s$  is a measure of the shape efficiency of the rotor in the stress-limited case.

The case of anisotropic materials, such as carbon composite, is not as straight forward, may be illustrated by the following example. For ideal composite rotors, the analysis is more complicated because the maximum stress depends not only on the rotor shape, but also on the composite material system(s), fabrication process, loading conditions, and other factors such as failure modes. The maximum tangential stress,  $S_m$  in a long

Table 2  
Shape factor for various flywheel geometry

Flywheel geometry	Cross sectional/pictorial view	Shape factor $K_s$
Flat unpierced disc		0.61
Thin rim		0.50
Rim with web		0.40
Flat pierced disc		0.31

Table 3  
Specific energy ranking for various flywheel geometry

Flywheel geometry	Cross sectional/pictorial view	Specific energy $E_{sp}$
Thin rim		<div style="text-align: center;"> <math>\downarrow</math>  worst </div>
Rim with web		
Flat unpierced disc		
Flat pierced disc		

hollow cylinder of anisotropic material is given by

$$S_m = \frac{\rho \omega^2}{4(1-\nu)} [r_0^2(1-2\nu) + r_1^2(3-2\nu)] \quad (4)$$

where  $r_0$ ,  $r_1$ , are the inner and outer radius respectively and  $\nu$  is Poisson's ratio. This value may then be fed into Eq. (1) to give the specific energy of the cylinder:

$$E_{sp} = \frac{(r_1^2 + r_0^2)S_m}{\rho((3-2\nu/1-2\nu)(r_1^2 - r_0^2) + 4r_0^2)} \quad (5)$$

Similarly, for a disk shaped rotor, the maximum tangential stress is given by

$$S_m = \frac{3+\nu}{9} \rho \omega^2 r_1^2 \quad (6)$$

Thus, the specific energy is given by

$$E_{sp} = \frac{2S_m}{\rho(3+\nu)} \quad (7)$$

Table 3 illustrates that a hollow cylinder has higher specific energy.

### 2.3. Flywheel length

The previous section explains how the optimum rotor cross-section can be designed, however it does not determine how long the flywheel should be. The optimal length is directly related to dynamic considerations. A rotating body may undergo both rigid body and flexural resonance modes (criticals). If the bearing system is very stiff, all of these criticals will occur above the operating frequency of the rotor. This however leads to high losses. Thus, a bearing system is chosen which is soft enough to ensure that the rigid body criticals are passed at low speed. Once the criticals have been passed on run-up, the rotor will spin about its centre of mass with low damping losses and low forces on the bearing system. This is only possible with a highly balanced rotor which has a low mass centre shift. With the bearing stiffness chosen, the

length of the rotor affects the conical rigid body mode. The length to diameter ratio of the rotor is specifically chosen to be significantly greater or less than 1:1 to avoid exciting this mode in the cycling range of the machine. Thus, the choice is between a disc and a cylinder. The length is simply chosen to be the maximum safe length below the speed of the rotor when it is running at its speed of maximum stress.

### 2.4. Bearings

The spinning rotor must be supported on bearings. Initially, both ball bearings and magnetic bearings were considered (Table 4). The important parameters in assessing the use of ball bearings or magnetic bearings are weight, loss, cost, lifecycle life, and low losses. They also can isolate rotor and stiffness. Magnetic bearings can accommodate very high spin speeds and have theoretically unlimited imbalance induced vibrations. Ball bearings have benefited greatly from material advances such as ceramics and very hard steels. The main life issues are not material fatigue life, but rather lubricant life. Lubricant life depends primarily on temperature. Bearing life is essentially unlimited if temperatures are kept low and the lubricant does not deteriorate. In general, an upper bound on the spin speed exists above which magnetic bearings are better. Below this bound, ball bearings have a weight advantage because the drag losses are relatively low. This bound is application dependent, but generally falls between 20,000 and 40,000 rpm [8].

Recently, high temperature superconducting (HTS) bearings were used in FES, which could contribute significantly to lower loss [14,15]. HTS bearings have the potential to reduce rotor idling losses and make flywheel energy storage economical [16]. Very low frictional coefficients can be achieved in the order of  $10^{-6}$  or even smaller [3]. This very small frictional coefficient makes flywheels with HTS bearings as kinetic energy storages with very low losses. Its hysteresis loss at 3000 rpm was calculated to be 0.5 W according to the model, and the sum of eddy current losses at the same speed was 2.5 W [8]. A system consisting of an HTS-based levitated flywheel as the energy storage unit and solar cells as the power supply was installed and investigated as a model of a viable variant of the mini power plant concept [17].

## 3. Applications of FES

### 3.1. FES in space

One application to which FES is of great concern is on the International Space Station (ISS) [4,8]. Its primary power

Table 4  
A basic comparison of the bearings

Bearing type	Approximate power loss (30 kg rotor)	Advantages	Disadvantages
Ball	5–200 W + due to seals	Simple, low cost, compact	Needs lubrication, seals, hubs and axle
Magnetic	10–100 W	Acts directly on rotor, can cope with clearance changes	High cost, requires “touchdown bearings” reliability
HTS	10–50 W	Low loss, high forces	Long-term development requirement, house keeping losses

source is the sun, but the station can continue to operate via FES while in eclipse. Flywheel for energy storage in ISS was first discussed in 1961 and Integrated Power and Attitude Control Systems (IPACS) for satellites were first proposed in the 1970s [8]. In the mid-1990s there was renewed interest in flywheel energy storage and IPACS concepts [7], based on advances in magnetic bearings and high-strength composite fibers, which evolved independently. In 1994, The NASA Glenn Research Center (then Lewis Research Center) devoted new efforts to develop flywheel systems on satellites. A cooperative effort with the Space Vehicles Directorate of the Air Force Research Laboratory (then Phillips Laboratory) to develop flywheel technology for satellite applications was initiated [18]. For the past decade, the NASA Glenn Research Center (GRC) (formerly LeRC) has been interested primarily in developing flywheel energy storage capability, with a secondary interest in the attitude control potential [9]. Recent interest in space applications of flywheel energy storage has been driven by limitations of chemical batteries for Air Force and NASA mission concepts. FES was designed to replace the nickel hydrogen (NiH<sub>2</sub>) battery orbital replacement units in the ISS Electric Power System. Combining the functionality of two subsystems addresses the industry's continuing desire to improve efficiency and reduce spacecraft mass and cost. Each NASA flywheel unit will store in excess of 15 MJ and can deliver a peak power of more than 4.1 kW [8]. NASA estimates that more than US\$ 200 million will be saved if flywheels replace the first generation of space station batteries [11]. Ref. [19] presents a system consisting of a double counter rotating flywheel unit serving for the satellite energy and attitude management.

### 3.2. FES in vehicle

The basic idea of FES packed in vehicle is that the average power needed to propel the vehicle should be supplied by the engine, which can therefore operate at a nearly constant, optimum speed, reducing fuel consumption, air and noise pollution, and engine maintenance requirements, and extending engine life [20]. Short bursts of power, for climbing hills and acceleration, are taken from FES, which is replenished directly by the engine or by regenerative braking when the vehicle is slowed down [21–23]. Unlike friction brakes, which turn kinetic energy into waste heat, regenerative braking changes it to speed up the flywheel for subsequent acceleration. FES packed in a hybrid electric bus is being tested at the University of Texas at Austin. The unit can accelerate a fully loaded bus to 100 km/h, stores about 7.2 MJ, and has a peak power capability of 150 kW, as well as a specific energy of more than 120 kJ/kg of rotating mass and a specific power of 2.5 kW/kg of rotating mass [3]. Ref. [24] proposed a novel flywheel-engine hybrid system employed Constant Pressure System (CPS) to replace complex systems such as a planetary gear set or Continuously Variable Transmissions (CVTs). The US Federal Railroad Administration also has a program to develop FES for high-speed rail applications. To overcome 'jet-start' of powertrain, a CVT powertrain is augmented with a planetary gear set and

compact steel flywheel [25,26]. By employing the flywheel as energy regeneration, the electric power consumption rate of the vehicle can be 188 km/L in the community-driving schedule, and over 50 km/L in the long driving schedules [27].

In addition, hybrid electric power is an essential enabling technology for many future combat vehicles [28]. The US Department of Defense envisions future combat vehicles as having electric propulsion as well as suspension, communications, weapons, and defensive systems—all needing electric power. Flywheels provide both continuous and pulsed power for the various systems on the vehicle distribution networks subsystem controls and power-conditioning devices.

### 3.3. FES in power source

The combination of modern power electronics and flywheel can provide protection against the multiple short-voltage disturbances that are characteristic of a Power Quality event [29,30]. FES can serve to meet short-term, random fluctuations in demand and so avoid the need for frequency regulation. It can also provide 'ride through' for momentary power outages, reduce harmonic distortions, and eliminate voltage sags and surges. It accommodates the minute-hour peaks in the daily demand curve. Storage of surplus electricity generated overnight (i.e. during off-peak hours) to meet increased demand during the day [31]. Hence, companies in both Europe and the United States have developed systems and are distributing them worldwide. For example, Piller GmbH (Osterode, Germany) has installed flywheel energy storage in the combined heat and power station that supplies an AMD semiconductor fabrication facility in Dresden, Germany. The 3-year-old plant has an overall power rating of 30 MW; its multiple-flywheel storage subsystem can supply or absorb 5 MW for 5 s. Active Power (Austin, Texas) announced that it is delivering 17 flywheels with a combined power rating of 4.75 MW to a plastics product manufacturer, which needs them for power conditioning and to protect against outages [3]. The New Energy Development Organization (NEDO) in Japan is attempting to develop a 10 MWh commercial flywheel system for load leveling at electricity substations [2]. The 250-kVA flywheel UPS had been manufactured and performed well in a critical load, protecting the load from sags and momentary power outages [30].

Storage of electricity generated by renewables can match the fluctuating supply to the changing demand [2]. Referring back to the two World Energy Council (WEC), wind and photovoltaic sources together will contribute between 0.7 and 2.1 PWh of electricity to the world supply in 2020 [32]. Flywheels are of potential interest for the localized storage of electricity generated by wind turbines and photovoltaic arrays since the variable and intermittent nature of their output. A flywheel-based buffer store could remove the need for downstream power electronics to track such fluctuations and so improve the overall electrical efficiency [33,34]. Staff members at Clarkson University (Potsdam, NY) and the University of South Africa (Pretoria) are developing flywheel storage with a view to helping the nearly one-third of the



world's population without access to an electricity grid. Solar power, wind power, or diesel generators can supply these people with some electricity for refrigerating food and medicine and for communication [35].

### 3.4. Other applications

Another application of FES is in the launching of aircraft from carriers [28]. Today, launch catapults are driven by steam systems, which use steam accumulators to store enough energy for the job. The US Navy is developing electromagnetic systems in which flywheels could replace the steam accumulators so that the power-generating system would not have to be sized for the peak power load.

Clearly, FES is an emerging technology. Commercial versions are available for limited applications today, but the research and development now under way may stimulate much wider use. For instance, coupling a hydraulic system with a flywheel is used in lift equipment for potential energy recovery using pump/motor for hydraulic system to improve the system efficiency. Such as oil pump lifter, crane, hoist, hydraulic elevator and so on.

## 4. Issues of FES

### 4.1. Management of safety

A natural concern with flywheel energy storage is its safety [5]. For a few years now, several safety projects have been funded in the United States by the Defense Advanced Research Projects Agency, the Houston (Texas) Metro Transit Authority, and NASA. Safety challenge can be accommodated by three approaches. First, designed margins are verified to failure at speeds well above the rated speed. Achieving safe operation by derating the maximum speed is a common practice. The maximum allowable operating speed will be determined from destructive spin tests and dynamic stress analyses. The spin tests will establish the rotational speed of failure. The margin of safety will be established by analyses that evaluate how the stresses vary with speed. The maximum safe operating speed will be established by backing off from the rotational speed of failure. The second is fault protection. The operational control strategies will be integrated with the on-board computer and health monitoring sensors will be provided to evaluate the performance of all parameters of the FES, including structure, electromagnetic bearings, the motor/generator, and electronics [36]. Thus, they can be shut down safely if an abnormal condition should arise. Third is containment. The containment system is designed specifically for two types of failure associated with the flywheel: (i) an intact rotor failure, where the rotor remains essentially intact throughout the failure and (ii) a rotor fragmentation type failure, where the carbon composite layer shatters.

In an intact rotor failure, the rotor processes about the central shaft. The maximum (worst case) precession speed  $\Omega$  can be determined from the formula:

$$\Omega c = \omega r_1 \quad (8)$$

where  $c$  is the clearance between the rotor and the central shaft. Since  $r_1 \gg c$ , then there is the potential for very high precession speeds to occur and hence also very high bending moments (which are proportional to  $\Omega^2$ ).

In a rotor fragmentation type failure, the radial loading on the containment can be modeled mathematically using a crushing fragment analysis allowing the containment thickness to be optimized. The peak torque on the containment is approximately given by

$$T_0 = \frac{I\omega}{\tau} \quad (9)$$

where  $\tau$  is the half-stopping time of the rotor fragments. To control the crash loadings the failure, torque reduction and energy absorption is achieved by allowing the containment to turn against crush elements.

### 4.2. Management of losses

One of the important parameters of FES is the energy efficiency. The overall efficiency depends strongly on the losses. Flywheel must be rotating continuously overcoming its mechanical loss,  $P_{\text{loss}}$ , that consists of axial rotating loss,  $P_{\text{ax}}$ , windage loss,  $P_{\text{wind}}$ , copper loss,  $P_{\text{Cu}}$ , and iron core loss,  $P_{\text{Fe}}$  and can be calculated by Eq. (10).

$$P_{\text{loss}} = P_{\text{ax}} + P_{\text{wind}} + P_{\text{Cu}} + P_{\text{Fe}} \quad (10)$$

The windage loss amounts to a large ratio of the total losses [37], therefore windage loss reduction is the most effective and easiest way to reduce total holding loss of the flywheel and improve system efficiency. On the one hand, high-speed flywheels are generally mounted in vacuum enclosures, to eliminate air drag to reduce mechanical loss. Definitely installing these technologies can improve total efficiency. However, they would become complex devices and would be an expensive system like vacuum pump, chamber, and cooling system. From a thermal standpoint, vacuum condition is adverse to heat removing from the rotating parts of the flywheel system [5]. On the other hand, using helium–air mixture gas is a good way to reduce the windage loss. Ref. [37] demonstrates that in the case of 50 vol% helium per air, the drag reduced ratio decreases to 43% of that of air 100 vol%, and in case 75 vol% helium, over 70% loss can be reduced.

## 5. Conclusions

During the last century, energy sustainability and environment protection have urged the development of FES. Though it is multi-beneficial to many utilities and it offers significant operating cost savings to the ISS, the commercialization of FES was not very successful. The main reason was due to safety issues and high cost for industry. Looking ahead in the next few decades, with the aid of new technologies, FES will continue to develop and the key issue will be solved and reduced gradually. There are three major advancements that are considered for the next decade. The first is higher specific power density kW/kg and higher specific energy density Wh/kg. It is not unreasonable to

expect that future flywheel systems are projected to have the following performance characteristics: specific energy = 200 Wh/kg and specific power = 30 kW/kg. the second is to improve its efficiency by reduction of loss. Helium–air mixture gas condition or Vacuum enclosure with better heat exchangers will be selected according to different operation condition. The last is prediction design and intelligent fault protection will be enhanced for system safety, which requiring development of new software and checkout procedures. If the cost of FES can be lowered, they will be widely used both in civil and military industries and play a significant role in securing global energy sustainability.

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